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Simulating the Formation and Evolution of Behind Armor Debris Fields

by Stephen J. Schraml, Hubert W. Meyer, David S. Kleponis, and Kent D. Kimsey

ARL-RP-109 **November 2005**

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14. ABSTRACT
The performance of the CTH shock physics code was evaluated on the Opteron cluster recently installed at the U.S. Army Research Laboratory (ARL) Major Shared Resource Center. Scalability trials were conducted using up to 2048 processors and involved the simulation of the yawed, oblique impact of a long rod penetrator with a thin plate. The scalability of CTH on the Opteron cluster was studied for both fixed and adaptive meshes. After the scalability study was completed, CTH simulations were conducted to evaluate the potential to use shock physics simulations to augment experimental data in behind armor debris applications. These simulations were conducted for both fixed and adaptive meshes. A variation of a fracture model currently under development at ARL was also evaluated.

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1. Introduction

Under the auspices of a DoD High Performance Computing Modernization Program (HPCMP) Capability Applications Project (CAP), researchers at the U.S. Army Research Laboratory (ARL) evaluated the performance of the CTH shock physics code[1] on the Opteron cluster recently installed at the ARL Major Shared Resource Center (MSRC). This system has 2304 processors for batch processing, each running at a clock speed of 2.2 GHz. Scalability trials were conducted using up to 2048 processors and involved the simulation of the yawed, oblique impact of a long rod penetrator with a thin plate. This case has been used in the past as a standard benchmark in assessing the scalability of CTH on many other scalable systems deployed by HPCMP[2, 3, 4, 5, 6, 7, 8]. The scalability of CTH on the Opteron cluster was studied for both fixed and adaptive meshes.

After the scalability study was completed, CTH simulations were conducted to evaluate the potential to use shock physics simulations to augment experimental data in behind armor debris applications. These simulations were conducted for both fixed and adaptive meshes using 512 – 2048 processors. A variation of a fracture model currently under development at ARL was also evaluated.

This paper describes the scalability of CTH on the Opteron cluster and the results of a set of simulations to model the formation and evolution of behind armor debris fields.

2. Scalability Study

The scalability of CTH on an Opteron cluster (Stryker) was determined through a series of simulations that employed both fixed and adaptive meshes. The fixed-mesh scalability simulations were conducted with a nearly constant workload. This was done to keep the computation-to-communication ratio as close to constant as possible for simulations involving different numbers of processors. Maintaining a nearly constant computation-to-communication ratio and minimizing disk access for intermediate plot and restart files during the time integration permitted the computational performance to be isolated and measured as a function of the number of processors used.

As the number of processors was increased, the fixed mesh was incrementally refined by uniformly decreasing the characteristic cell size in each coordinate direction by the nearest integer factor of $2^{-1/3}$. This approach approximately doubles the total number of Eulerian cells with each successive mesh refinement. The characteristics of the meshes used in the scalability study are summarized in Table 1. In this table, the columns NI, NJ, and NK refer to the number of Eulerian cells in the x, y, and z directions, respectively. The mesh sizes listed in the table produce computational sub-domains containing approximately 387,000 Eulerian cells each. For the 2048-processor simulation, this results in a computational domain containing approximately 800 million Eulerian cells.

The scalable performance of the message-passing code is measured by the "grind time," which is the average processor time required for the code to update all field variables for one computational cell in a given time increment (cycle). In a case of ideal scalability, the grind time will decrease by a factor of two for every doubling of processors used if the ratio of computation to communication is held constant.

Table 1. Fixed-mesh CTH scalability study parameters.

Number of Processors	NI	NJ	NK	Total Cells	Cell Size (mm)
1	215	30	60	387,000	1.0000
2	271	38	75	772,350	0.7934
4	341	48	95	1,554,960	0.6305
8	430	60	120	3,096,000	0.5000
16	541	76	151	6,208,516	0.3974
32	683	95	191	12,393,035	0.3148
64	860	120	240	24,768,000	0.2500
128	1083	151	302	49,386,966	0.1985
256	1366	190	382	99,144,280	0.1574
512	1720	240	480	198,144,000	0.1250
1024	2166	302	604	395,095,728	0.0993
2048	2732	380	764	793,154,240	0.0787

The results of the fixed-mesh CTH scalability study are presented in Figure 1. This figure compares the performance of Stryker to that of two other ARL MSRC clusters: the 32-processor prototype Opteron cluster (Cage) and the 256-processor, 3.06-GHz Xeon cluster (Powell). Each of these clusters has two processors per node. Simulations were performed using both 1 and 2 CTH tasks per node.

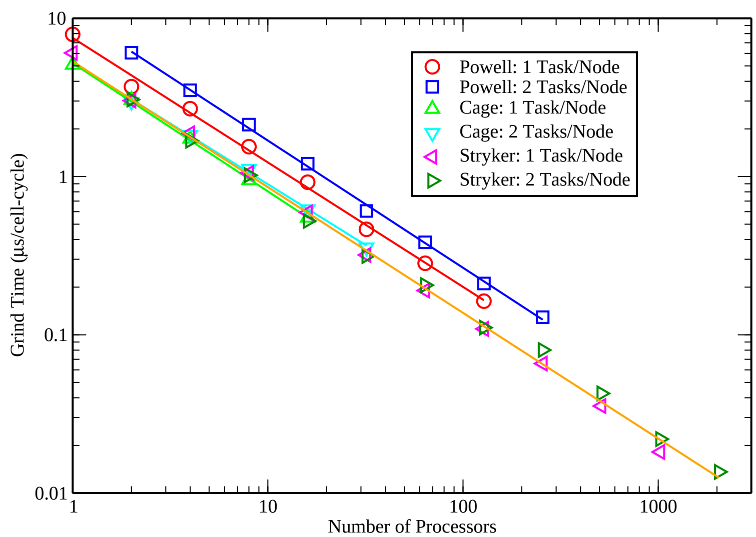

Figure 1. Scalable performance of fixed-mesh CTH on Opteron & Xeon clusters.

The fixed-mesh CTH scalability results show that the performance on Stryker is approximately the same as that on Cage, the prototype system. The 2-task/node performance on the Opteron systems was almost the same as the 1-task/node performance. The same is not true for the Xeon-based system (Powell) in which the 2-task/node performance is less than that of the 1-task/node. Linear scalability was obtained on Stryker for all simulations up to the largest case using 2048 processors. The orange line in Figure 1 is the result of a regression analysis of the data from the 1- and 2-task/node runs on Stryker which resulted in a parallel efficiency of approximately 79%.

An adaptive mesh refinement (AMR) capability has been added to CTH which allows the definition of the mesh to change during the simulation based on the evolving characteristics of the simulation[9]. The adaptation of the mesh is based on user-defined indicators, such as the value, gradient, or difference, of

a variable in the solution (pressure, density, velocity, stress, etc.). This technique results in simulations in which the most highly resolved mesh "follows" the activity of interest to the analyst while using less highly resolved mesh in the remainder of the computational domain. This allows the analyst to configure highly resolved simulations that have fewer total computational cells than a comparable fixed-mesh simulation having the same minimum cell size.

The AMR implementation in CTH is a block-based scheme in which each block consists of an orthogonal mesh with a fixed number of cells in the x, y, and z directions. The blocks are connected in a hierarchal manner with adjacent blocks having either exactly the same cell size or exactly a 2:1 ratio in cell size. Refinement or un-refinement of the mesh is accomplished through a series of transitions of adjacent blocks with a difference in mesh density of 2:1. All mesh blocks at a given mesh density are at the same refinement level. The finest mesh resolution that can exist in the computational domain is controlled by defining the maximum refinement level of the mesh.

The AMR CTH benchmark used in the scalability study was configured to be physically identical to the fixed-mesh simulation. The only difference between the fixed-mesh simulation and the AMR simulation was the definition of the mesh. The size of the mesh in the AMR simulation was scaled with the number of processors in a manner similar to the fixed-mesh study. However, it is not possible to precisely scale the total number of cells in the AMR simulation since the refinement and un-refinement indicators are based on the physics, not the topology of the computational domain. Thus, to scale the size of the simulation in a controlled manner, the maximum refinement level was increased by one for every factor of eight increase in the number of processors. The 2:1 ratio of cell size between refinement levels results in a factor of approximately eight in the total number of cells in the 3-D simulation. The variation of the maximum refinement level and the resulting minimum cell size with the number of processors used is summarized in Table 2.

Table 2. AMR CTH scalability study parameters.

Number of Processors	Maximum Refinement Level	Minimum Cell Size (mm)
1	4	1.875
2	4	1.875
4	4	1.875
8	5	0.938
16	5	0.938
32	5	0.938
64	6	0.469
128	6	0.469
256	6	0.469
512	7	0.234
1024	7	0.234
2048	7	0.234

The results of the AMR CTH scalability study are provided in Figure 2. This figure compares the grind time vs. number of processors used for Stryker and Powell (an AMR scalability study was not conducted on Cage). The results of the AMR study show the same trends as the fixed-mesh study, with Stryker demonstrating a parallel efficiency of approximately 80%. On the Xeon-based system, there is a clear difference between the 1- and 2-task/node performance, while there is not a noticeable difference on the Opteron-based system. As in the fixed-mesh study, linear scalability was achieved for all simulations up to the maximum of 2048 processors in the study.

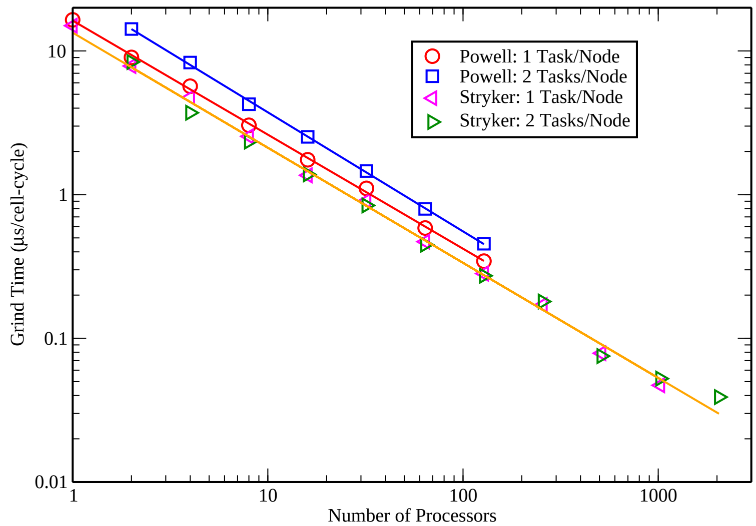

Figure 2. Scalable performance of AMR CTH on Opteron & Xeon clusters.

3. Behind Armor Debris Study

Behind armor debris is a major cause of damage in military vehicles that have been perforated by a penetrator, bullet or fragment. The ability to predict the debris field resulting from attack by such a threat is critical to assessing and improving the survivability of tactical systems. The ARL Survivability and Lethality Analysis Directorate (SLAD) has the mission of providing such assessments to vehicle designers. The ARL Weapons and Materials Research Directorate (WMRD) has been working to develop the capability to model numerically the behind armor debris resulting from armor perforation, for application to the SLAD mission.

Modeling of the debris field historically has been done by statistically analyzing data from carefully controlled experiments. The difficulty of collecting this information makes it an expensive and lengthy process. Supplementing these experiments with numerical simulations is a natural synergy, but has not yet been successfully exploited because previous computer systems were unable to cope with the daunting size of the simulations.

With the addition of the Opteron cluster to the ARL MSRC, numerical modeling of these experiments is now within reach. The experiment modeled as a demonstration of the technique consists of a 30-mm Armor Piercing Discarding Sabot (APDS) round perforating a 1-inch-thick armor steel plate. The resulting behind armor debris impacts a large (610-mm x 610-mm) [2-ft x 2-ft], thin (0.8-mm) [1/32-inch] mild steel witness plate placed 610 mm behind the armor. Perforations made in the witness plate by the debris are measured, and conclusions drawn about the size, mass, spatial distribution and velocity of the debris field. This is painstaking work, but it results in a reasonably accurate characterization of the debris field.

The difficulty in modeling this experiment arises primarily from two factors. First, the experiment is inherently three-dimensional in nature due to the random distribution of failure in the plate. Thus any simulation of the experiment must be done in three dimensions (3-D). Second, the wide range of length scales requires a fine mesh resolution to resolve the debris field that, when extended over the 610-mm air space and large area of the witness plate, requires approximately one-half billion cells for a relatively coarse resolution (two cells through the thickness of the witness plate). Compounding the problem, the small cell size requires a small integration time-step, so a huge number of computation cycles is required to traverse the debris through the 610-mm air space.

The result of modeling such an experiment with CTH can be seen in Figure 3a, which shows the state at 600 μs after impact of the 30-mm APDS round on the armor plate, when the debris field is well developed but has not yet impacted the witness plate. This 3-D simulation ran on the Opteron cluster using 2048 processors, or 9 teraflops of compute power. To run the simulation to 1.2 ms, when most debris has perforated the witness plate, required five days, the equivalent of over 28 processor-years. The simulation required more than 1 TB of memory, and generated over 300 GB of field data to disk. A few years ago, running this simulation would not have been possible.

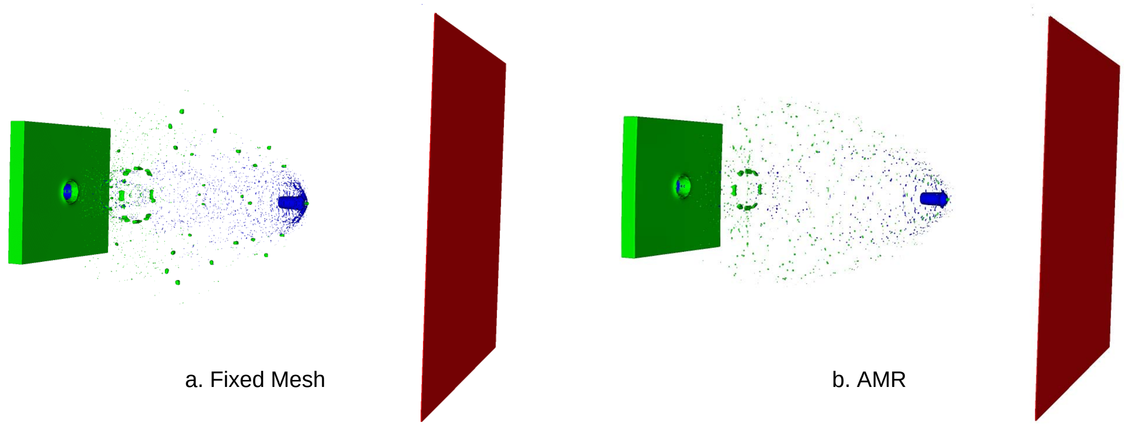

Figure 3. CTH simulations of behind armor debris experiment, 600 μs after impact: a. fixed mesh, b. AMR.

It is possible to reduce the size of this simulation by employing the AMR technique in CTH. When AMR is employed, the mesh is refined only in regions of interest. As a result, the large empty areas of this simulation are coarsely resolved, and mesh refinement follows the fragments in the debris field as they fly toward the witness plate. The state of the AMR simulation at 600 μs is shown in Figure 3b. This 3-D simulation ran for 54 hours on 512 processors using a total of 0.5 TB of memory. This is a very large simulation, but almost one-tenth the processor-hours of the fixed-mesh simulation in Figure 3a.

One objective of the current work was to verify that the AMR CTH simulation will produce the same result as the fixed-mesh simulation. The work showed that mesh resolution in CTH has an impact on the predicted fragmentation, and must be carefully controlled. A difference between the finest resolution of target material in the AMR simulation (Figure 3b) and the constant resolution of the fixed-mesh simulation (Figure 3a) contributed to the differences seen in the debris field. If resolution is consistent, AMR CTH was found to be an accurate and computationally effective substitute for the fixed-mesh case. Another objective of this work was to verify the ability to run CTH on large-scale clusters to efficiently conduct extremely large computations on a large number of processors. This work provided a realistic test that demonstrated scalability.

In the second part of the behind armor debris study, a fracture model was modified to improve the CTH prediction. Researchers at the Lawrence Livermore National Laboratory (LLNL)[10] have demonstrated with a Lagrangian code the effectiveness of providing a statistical distribution of fracture properties in simulations. Here, the technique is incorporated into the Eulerian code CTH and applied to modeling this ballistic experiment. In a conventional CTH simulation, all cells containing target material have the same set of fracture model parameters, so all fail in the same way. This effect is shown graphically in Figure 4a, which shows the bulge on the rear of the target plate just prior to the penetrator breaking through. Damage is shown in this figure by coloring; blue is no damage, red is fully damaged. Notice the uniformity and symmetry of the damage in the bulge. The new model installed in CTH provides a spatially random distribution of values for the principal fracture model parameter, although in the aggregate its population is Weibull-distributed. This causes non-uniform, stochastic failure of the armor plate, as shown in Figure 4b. The resultant behind armor debris field is strongly dependent on the nature of the Weibull distribution of the fracture parameter, as quantified by the Weibull modulus, m, which is a user-supplied input to CTH.

As an analogy, think of the Weibull modulus as determining the standard deviation of the distribution of the fracture model parameter. A Weibull modulus of $m = 2$ provided the results shown in Figure 4b. As can be seen by comparing Figures 4a and 4b, a more realistic fragmentation of the target is obtained with the distributed fracture parameter approach.

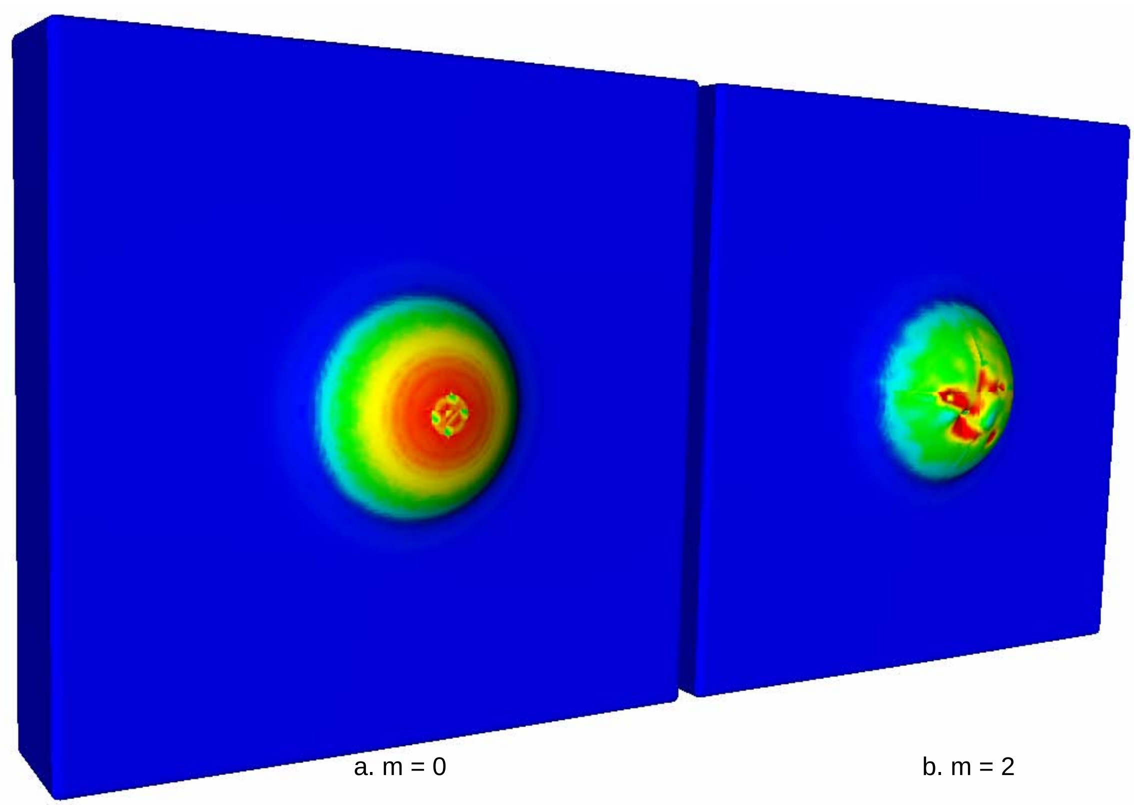

Figure 4. Bulge of the rear of the target plate showing damage just prior to break-out (60 μs after impact) for Weibull modulus of: a. $m = 0$, b. $m = 2$.

In a third part of this work, Jerry Clarke of the ARL Computational and Information Sciences Directorate (CISD) is developing software based on the Interdisciplinary Computing Environment (ICE) which will automatically identify and quantify all contiguous bodies in a CTH calculation. This type of automatic analysis was not previously possible with CTH calculations. Called FragFinder, this software identifies regions (i.e., fragments) where the volume fraction for each material is above a certain threshold, and determines the volume and velocity of these regions. FragFinder was used to analyze the debris field in a conventional CTH simulation ($m = 0$) and in a CTH simulation using statistical fracture ($m = 2$). The results are presented in Figure 5, where the volume determination has been converted to mass. This plot shows the total number of fragments, from both the penetrator and the target, with a mass greater than or equal to a given (abscissa) value. The open symbols show the experimental data. The dashed line shows the result for standard CTH, which over-predicted the number of fragments, especially the number of small fragments. The solid line shows the result of a simulation using the statistical model (with m=2) for the target only, a significantly improved result. Figure 5 indicates that with the proper choice of Weibull modulus, and with the statistical model applied to both the target and the penetrator, a more realistic debris field can be obtained than arises from the classic method of using a constant parameter.

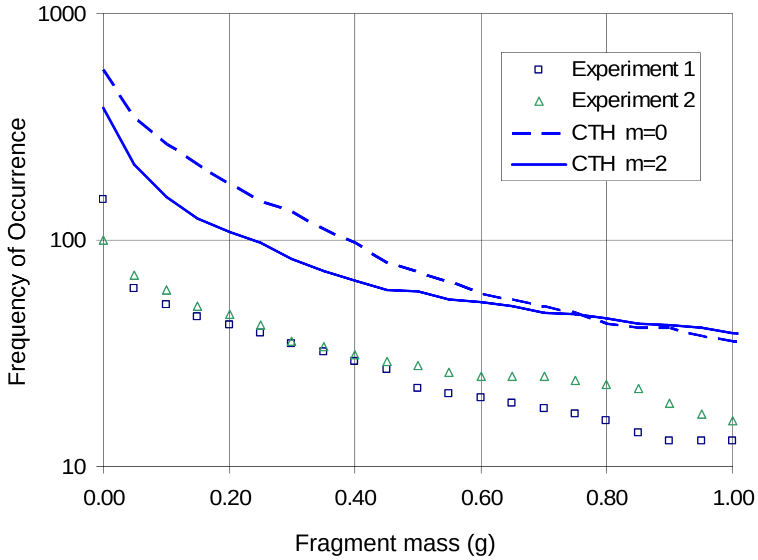

Figure 5. CTH prediction of mass distribution of fragments compared to experimental results.

4. Summary

The linear scalability of CTH on the ARL MSRC Opteron cluster has been demonstrated for simulations using up to 2048 processors. The linear scalability was demonstrated for simulations using both fixed and adaptive meshes. As a result, the general efficacy of large scale weapons effects simulations on scalable systems has been demonstrated.

The work described herein has also shown that numerical simulation of behind armor debris is now within the ability of current MSRC resources, and simulations can be successfully exploited to supplement the expensive experiments. Furthermore, the new capabilities of statistical fracture and automatic fragment quantification make the technique more useful.

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References

[1] McGlaun, J.M. and S.L. Thompson. "CTH: A Three-Dimensional Shock Wave Physics Code." *International Journal of Impact Engineering*, 1990, **10**, 351-360.

[2] Kimsey, K.D., S.J. Schraml, and E.S. Hertel. "Scalable Computations in Penetration Mechanics." *International Journal on Advances in Engineering Software including Computing Systems in Engineering*, 1998, **29**, 209-215.

[3] Schraml, S.J. and K.D. Kimsey. "Scalability of the CTH Hydrodynamics Code on the Sun HPC 1000 Architecture." U.S. Army Research Laboratory, ARL-TR-2173, February 2000.

[4] Schraml, S.J. and K.D. Kimsey. "Large Scale Impact/Penetration Simulations on Clustered Symmetric Multiprocessors." Proceedings of the 2000 International Symposium on Parallel and Distributed Processing Techniques and Applications. Las Vegas, NV, June 2000.

[5] Schraml, S.J., K.D. Kimsey, and T.M. Kendall. "Scalable Simulations of Penetration Mechanics on the SGI Origin 3800 and the IBM SP Power3 Computer Systems." U.S. Army Research Laboratory, ARL-TR-2537, June 2001.

[6] Schraml, S.J., K.D. Kimsey, and T.M. Kendall. "Scalable Simulations of Impact and Wave Propagation on Two New Parallel Computer Architectures." Proceedings of the 2001 International Symposium on Parallel and Distributed Processing Techniques and Applications. Las Vegas, NV, June 2001.

[7] Schraml, S.J., K.D. Kimsey, and J.A. Clarke. "High-Performance Computing Applications for Survivability-Lethality Technologies." *Computing in Science and Engineering*, Volume 4, Number 2, March 2002.

[8] Kendall, T.M., C.M. McCraney, and S.J. Schraml. "Early Experience With the IBM Power4 Scalable Parallel System at the ARL MSRC." Proceedings of the 2002 DoD High Performance Computing User's Group Conference, Austin, TX, June 2002.

[9] Bell, R.L., R.M. Baer, R.M. Brannon, D.A. Crawford, M.G. Elrick, E.S. Hertel, R.G. Schmitt, S.A. Silling, and P.A. Taylor. "CTH User's Manual and Input Instructions, Version 7.0." Sandia National Laboratories, Albuquerque, NM, April 2005.

[10] Springer, H.K. R.C. Becker, and R.Couch. "Fragmentation Modeling of Ductile with Heterogeneous Microstructure." DoE Tri-Lab Engineering Conference, Santa Fe, NM, 2003.

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